Retrofitting existing office buildings towards life-cycle net-zero energy and carbon

Background: Energy devices for achieving net-zero operating energy and carbon generally entails additional embodied energy and carbon during the production and disposal stages. For a building to be considered as truly life-cycle net-zero, the energy use or greenhouse gas emissions occurring across each stage of its life span must be offset. Retrofitting design approach for strict life-cycle net-zero buildings is still quite rare.

Method and innovation: The innovation of this study is to propose an integrated design process to determine optimal retrofitting solutions and achieve life-cycle net-zero. The retrofitting also aims at maximising lifetime payback cost by selecting appropriate installation areas or capacities of each renewable energy device. A real-world office building is adopted as a case study to demonstrate the proposed retrofitting design approach, while 5 different sceneries are adopted to demonstrate different retrofitting situations.

Results and implication: The maximum lifetime payback cost reduction would be 116.3% and 103.5% for life-cycle net-zero energy and carbon for this case study building. The proposed integrated design process can be applied to different types of buildings to transform them into truly carbon-neutral and consequently mitigate climate change-related issues.

Keywords:

Life-cycle net-zero; Office building; Building retrofitting; Life cycle assessment; Embodied carbon; Renewable energy.

1. Introduction, innovation and significance

In Europe, the building sector is responsible for 19% of the energy-related carbon emissions [1] and 36% of the total carbon emissions [2]. It is vital to retrofit and decarbonise existing buildings [3-5]. The criteria of good energy performance buildings vary substantially among European countries [6]. Most European countries aim at minimising primary energy use and greenhouse gas emissions at the operating stage [7]. In fact, Satola *et al.* [24] pointed out that it is essential to decrease greenhouse gas emissions during the processes of materials production, construction, operating, maintenance, and end-of-life demolition of buildings. U.K Green Building Council (UKGBC) [25] pointed out that life-cycle net-zero refers to the fact that the total amount of greenhouse gas emissions associated with the embodied and operational impacts over the entire lifespan of the building are not larger than zero. Therefore, the innovation of this paper is to propose an integrated design process to transform existing office buildings into **life-cycle net-zero energy consumption or greenhouse gas emissions** while maximising lifetime payback cost. It is expected that the proposed integrated design process can be applied to different types of buildings to transform them into truly carbon-neutral and consequently mitigate climate change-related issues.

2. Literature review

Most conventional net-zero retrofitting projects focused on realising net-zero operating energy. Ferrari *et al.* [8] explored various retrofitting options for an existing office building. The retrofitting target was to achieve better energy performance and reduce **operating** primary energy demand close to zero. The investigated retrofitting options included implementation of thermal insulation envelope; replacement of air conditioning system; installation of advanced controls of lighting systems and photovoltaic (PV) panels. Alkhateeb *et al.* [9] assessed the feasibility of converting an existing federal office building toward net-zero **operating** electricity consumption via envelope insulation and integration of a grid-connected PV system. Joao *et al.* [10] proposed retrofitting guidelines for transforming office buildings under different climatic conditions into net-zero **operating** energy buildings. Alternative building design parameters included external obstruction, shape factor, window-to-wall ratio, window type, efficient lighting system, natural ventilation, and rooftop PV panels. Escandon *et al.* [11] evaluated the energy performance and optimisation perspective of Dutch housing stock. An integrated façade renovation and renewable energy devices installation was adopted for achieving near-zero **operating** energy consumption in this stock. The adopted retrofitting options included increasing the insulation thickness, adoption of forced night-time ventilation for passive cooling and PV panel. Martin *et al.* [12] evaluated the possibility of transforming an old multi-family house into a near-zero **operating** energy building. The retrofitting options included the installation of interior insulation, retrofitting of windows, and installation of the decentralised mechanical ventilation system. Marwa *et al.* [13] assessed the possibility of retrofitting an off-grid vernacular building into a near-zero **operating** energy building through rooftop solar panels. Huang *et al.* [14] demonstrated that it is possible for an existing high-rise residential building to reach the **operating** passive house standard in northern China. The retrofitting options included fabric refurbishment and air conditioning system updating. Ajla *et al.* [15] investigated the feasibility of reducing **operating** energy of existing commercial buildings to net-zero through improvements in envelope insulation, replacement of lighting and air conditioning systems, as well as the installation of PV panels, wind turbines, and biomass boilers. Tang *et al.* [16] evaluated the optimal retrofitting resolutions for converting residential buildings into net-zero **operating** energy while considering the minimum thermal inconvenience or the highest economic performance. The retrofitting choices included insulating envelopes, replacing single-glazing windows, replacing the low-efficient boiler, and installing mechanical ventilation using a cross-flow heat recovery system. Asaee *et al.* [17] conducted a techno-economic analysis on retrofitting Canadian houses into net-zero **operating** energy consumption. The refurbishment measures included envelope insulation, appliance, and lighting up-gradation, as well as phase change material thermal storage installation. Paul *et al.* [18] explored the optimal retrofitting packages to improve building thermal performance and convert the gas-heated semi-detached houses in Ireland into near-zero **operating** energy. The retrofitting packages included insulating roofs and walls, installing triple-glazing windows, PV panels, and solar collectors. Sun *et al.* [19] evaluated the energy efficiency of a practical net-zero **operating** energy building in the tropical climate, which was retrofitted from an existing campus building by incorporating various passive and active design strategies. It was found that the most effective energy-saving measures included efficient lighting, efficient air conditioning system, lighting pies, lighting control and solar chimney ventilation. Rabani *et al*. [20] presented an optimisation method for minimising the energy use in a simulated office building stock in Norway and achieving net-zero **operating** energy use. The visual and thermal conditions were also considered. The retrofitting options included envelope insulation, air conditioning system, shading and fenestration devices. Shea *et al.* [21] analysed the cost-effectiveness of converting a university building into a fully-electrified, renewable energy-based net-zero carbon building during its **operating** stage. The retrofitting options included light-emitting diode lamps, air handling units for pre-conditioning outdoor air, and on-site PV panels. However, these research works focused on retrofitting with the target of net-zero operating energy use and carbon emissions, as defined by U.S. Department of Energy (USDOE) [22]. In other words, the net-zero operating energy is based on the criteria that the yearly primary energy consumption is not larger than the on-site exported renewable energy production.

Crawford *et al.* [26] found that a PV panel of 14.9 kW rated output is needed to offset all of the emissions associated with an average-sized new detached house in Melbourne, Australia. PV panel was the only retrofitting option of this study. It might not achieve the optimal lifetime payback costs, while there may not be sufficient installation area for such large PV panels. Sotola *et al.* [28] also demonstrated that it was possible to realise life-cycle net-zero primary energy use and greenhouse gas emissions for detached houses in Sydney using the PV system. It was also based on the assumption that there was unlimited installation areas for the PV panels. Birge *et al.* [27] evaluated the life-cycle greenhouse gas emissions related to villas and demonstrated that it was promising to realise life-cycle net-zero greenhouse gas emissions in the United Arab Emirates. Their design strategies included reducing the house size, installing insulation, using efficient appliances, using electric cars, and planting trees. However, reducing house size and planting trees may not be possible for most office buildings. Stephan *et al.* [29] appraised the possibility of realising life-cycle net-zero primary energy use and greenhouse gas emissions in apartment buildings through alternative architectural design. The alternative design included expanding polystyrene insulation on the outer walls and roof, installing solar thermal collectors, using light-emitting diodes, using energy-efficient electrical appliances and an electrical heater. However, this study was purely based on life cycle carbon assessment while life time payback cost is not considered.

Based on the above-mentioned literature review, the following significant research gaps are idenfied:

- Most state-of-the-art studies focused on retrofitting with the target of net-zero operating energy use and carbon emissions. In other words, the net-zero is based on the criteria that the yearly primary energy consumption is not larger than the on-site exported renewable energy production. However, if the entire life span is taken into account, the total energy consumption and carbon emissions of the net-zero buildings might still be positive. As investigated by Thiel et al [23], the global warming potential and embodied energy are 385 $kgCO_2/m^2$ and 5000 MJ/m^2 for the case-study net-zero energy office building.
- PV panel is considered as the single retrofitting option for achieving life-cycle net-zero. However, it requires large installation area and may not be possible for most of the office buildings.
- Those feasibility studies are based on life-cycle energy/carbon assessment, while lifetime payback cost is not considered.

Based on the identified research gaps, the unique contribution of this paper is to propose a retrofitting design approach to transform existing office buildings into **life-cycle net-zero energy consumption or greenhouse gas emissions** while maximising lifetime payback cost.

3. Research methodology: Integerated design process for LCNZE and LCNZC buildings

An integrated design process is proposed to determine optimal retrofitting solutions so as to achieve life-cycle net-zero. The objective of optimisation process is to maximise lifetime payback cost by selecting optimal installation areas or capacities of each renewable energy device. The pool of retrofitting measures, retrofitting design variables, retrofitting optimisation objective, retrofitting standard, and retrofitting evaluation criteria are smmuarised in this section.

Table 1. Catalogue of retrofitting options.

Retrofitting measures	References	Implemented in this study or not?	Reason?
Thermal insulation envelope on floor, wall and roof	8, 9, 11, 12, 14-18, 20, 27, 29	Implemented	Reduce heat loss
PV panels.	8-11, 13, 15, 18, 26		to generate electrical power using solar energy
Wind turbine	15		Implemented to generate electrical power using wind energy
Replacement of boiler or using a biomass boiler	15, 16		Biomass boiler is implemented to generate thermal power using renewable biomass and with a higher energy conversion ratio
Solar collector	18, 29		Implemented to generate thermal power using solar energy
Efficient air conditioning system	8, 11, 14-16, 18-21, 27	Not implemented	The efficient air conditioning system is already implemented
Efficient lighting system with advanced control	8, 10, 15, 17-21, 27		The efficient lighting system with sensor control is already implemented
External obstruction	10		It's not able to change due to local restrictions
Shape factor	10		It's not able to change due to the regulations of the case study building
Window-to-wall ratio	10		It's not able to change due to the regulations of the case study building
Window type	10, 13, 16, 18		Double-glazing windows have already been installed

3.1 Pool of retrofitting measures

The retrofitting measures adopted in previous works are summarised in Table 1, while some of them are adopted in this study. The reasons for whether they're selected are summarised in the fourth column. The design variables, optimisation objective and evaluation criteria are introduced in this section. the third column indicates whether there are implemented in this study.

3.2 Retrofitting design variables

The design variables include the design area of PV panel (A_{PV}), design area of solar heater (A_{SH}), rated power of wind turbine (A_{WT}), rated power of CHP system (A_{CHP}), and rated power of biomass boiler (A_{BB}).

3.3 Retrofitting optimisation objective

The optimisation objective is the lifetime payback cost (*LP_{COST}*) through those installed renewable energy devices. *LP_{COST}* indicates the lifetime cost-saving capability through retrofitting (i.e. the lifetime operating cost through existing building minus lifetime operating cost through retrofitting minus investment cost of retrofitting measures).

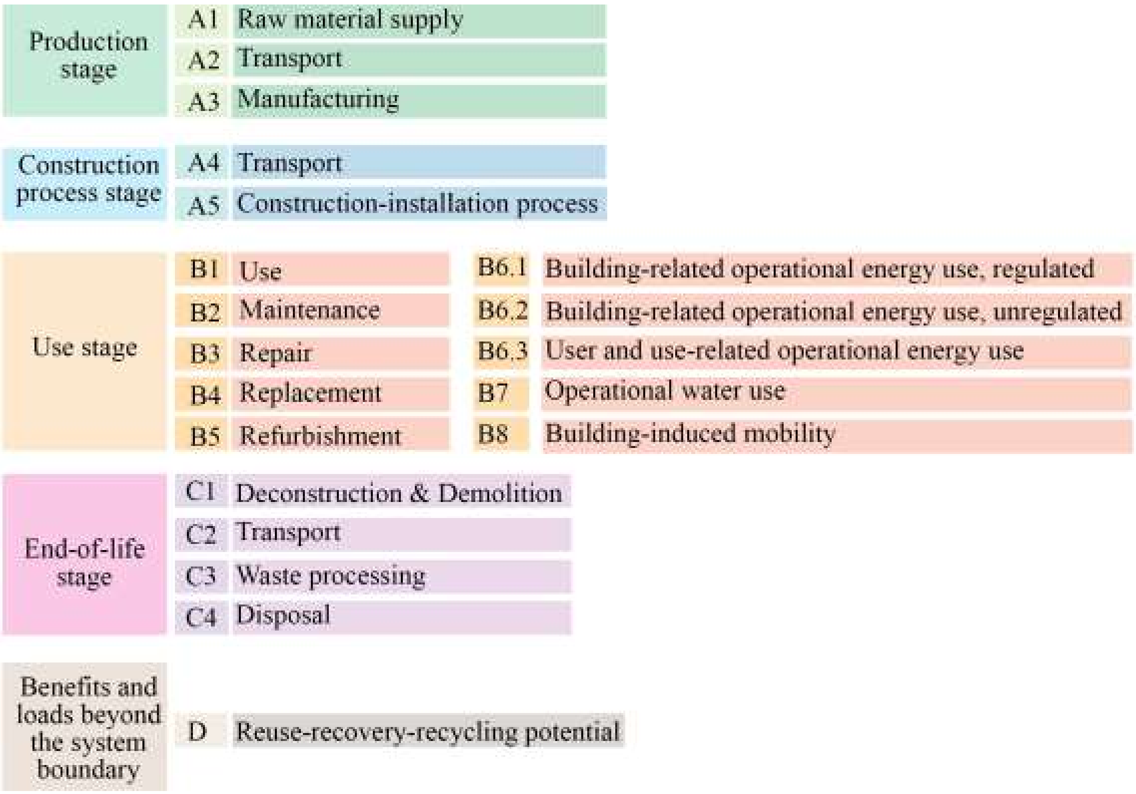
$$LP_{co} = (co_{ele}q_{PV}A_{PV} + co_{ele}q_{WT}A_{WT} + co_{ng}q_{SH}A_{SH} + co_{ele}q_{CHP,pr,e}A_{CHP} + co_{ng}q_{CHP,pr,h}A_{CHP} + co_{ng}q_{BB,pr,h}A_{BB} - co_{bio}q_{BB,con}A_{BB} - co_{bio}q_{CHP,con}A_{CHP}) \cdot LS - \left(co_{PV,r}A_{PV} + co_{SH,r}A_{SH} + co_{WT,r}A_{WT} + co_{CHP,r}A_{CHP} + co_{BB,r}A_{BB}\right) \quad (1)$$

where,

LS	Life span, which is assumed as 50 years as identified in most buildings.

co_{ng}, co_{ele}, co_{bio}	Unit cost factors of natural gas, electricity importation and biomass consumption (£/kWh)
q_{PV}, q_{WT}, q_{SH}	Yearly energy generated from PV panel, wind turbine and solar heater (kWh)
$q_{CHP,pr,h}$, $q_{CHP,pr,e}$	Year-round heat and electricity production from CHP system (kWh/kW)
$q_{BB,pr,h}$	Year-round heat production from biomass boiler (kWh/kW)
$q_{CHP,con}$, $q_{BB,con}$	Year-round biomass consumption of CHP system and biomass boiler (kWh/kW)
$co_{i,r}$	Investment cost of each renewable energy device. *i* refers to PV panel (PV), solar heater (SH), wind turbine (WT), combined heat and power system (CHP), and biomass boiler (BB), respectively. Here, the recurrent investment cost is considered. If the service life of a certain retrofitting measure is shorter than the life span (i.e. 50 years), the recurrent investment cost is considered by multiplying its investment cost according to its service life.

3.4 Retrofitting standard: Definition of life-cycle net-zero energy use and greenhouse gas emissions



Production stage	A1	Raw material supply		
	A2	Transport		
	A3	Manufacturing		
Construction process stage	A4	Transport		
	A5	Construction-installation process		
Use stage	B1	Use	B6.1	Building-related operational energy use, regulated
	B2	Maintenance	B6.2	Building-related operational energy use, unregulated
	B3	Repair	B6.3	User and use-related operational energy use
	B4	Replacement	B7	Operational water use
	B5	Refurbishment	B8	Building-induced mobility
End-of-life stage	C1	Deconstruction & Demolition		
	C2	Transport		
	C3	Waste processing		
	C4	Disposal		
Benefits and loads beyond the system boundary	D	Reuse-recovery-recycling potential		

Fig. 1. Life cycle information and boundary [33].

The determination of primary energy use and greenhouse gas emissions associated with a building's life cycle usually includes both the embodied and operational parts. The system boundaries of the building's life cycle are demonstrated in Fig. 1. The embodied part refers to the product stage (A1-A5), end-of-life stage (C1-C4), as well as benefits and loads outside the system boundary (D) [32]. The operational imapct refer to the use stage (B6.1-6.3). The aim of retrofitting is to achieve life-cycle net-zero energy (LCNZE) or life-cycle net-zero carbon (LCNZC). Net-zero achieving year (NZAY) is defined as how many years it is needed for the retrofitting solution's energy-saving performance to make up for its embodied energy and carbon.

3.4.1 Life-cycle net-zero energy (LCNZE)

LCNZE is defined on the principle that primary energy use reduction through adopting the retrofitting resolutions is larger than the total of embodied energy in the retrofitting materials and the building energy use over NZAY.

$$\begin{array}{c}\text{Primary energy}\\\text{usage reduction}\\\text{through retrofitting}\\\text{measures}\end{array} \times \begin{array}{c}\text{Years for}\\\text{achieing}\\\text{net-zero}\end{array} > \begin{array}{c}\text{Primary energy usagae of}\\\text{buidling operation at}\\\text{pre-retrofitting stage}\end{array} \times \begin{array}{c}\text{Years for}\\\text{achieing}\\\text{net-zero}\end{array} + \begin{array}{c}\text{Embodied energy}\\\text{of retrofitting}\\\text{materials}\end{array}$$

For PV panel and envelope insulation only,

$$e_{ele}q_{PV}A_{PV} \times NZAY > (e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{PV}A_{PV} + e_{INS}A_{INS}$$

For wind turbine and envelope insulation only,

$$e_{ele}q_{WT}A_{WT} \times NZAY > (e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{WT}A_{WT} + e_{INS}A_{INS}$$

For solar heater and envelope insulation only,

$$e_{ng}q_{SH}A_{SH} \times NZAY > (e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{SH}A_{SH} + e_{INS}A_{INS}$$

For biomass boiler and envelope insulation only,

$$(e_{ng}q_{BB,pr,h} - e_{bio}q_{BB,con})A_{BB} \times NZAY > (e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{BB}A_{BB} + e_{INS}A_{INS}$$

For CHP and envelope insulation only,

$$(e_{ele}q_{CHP,pr,e} + e_{ng}q_{CHP,pr,h} - e_{bio}q_{CHP,con})A_{CHP} \times NZAY > (e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{CHP}A_{CHP} + e_{INS}A_{INS}$$

For integrated adoption of different retrofitting options,

$$[e_{ele}(q_{PV}A_{PV} + q_{WT}A_{WT} + q_{CHP,pr,e}A_{CHP}) + e_{ng}(q_{SH}A_{SH} + q_{CHP,pr,h}A_{CHP} + q_{BB,pr,h}A_{BB}) - e_{bio}(q_{CHP,con} + q_{BB,con})] \times NZAY >$$
$$(e_{ele}q_e + e_{ng}q_{ng}) \times NZAY + e_{PV}A_{PV} + e_{WT}A_{WT} + e_{SH}A_{SH} + e_{CHP}A_{CHP} + e_{BB}A_{BB} + e_{INS}A_{INS}$$

where,

e_{ng}, e_{ele}, e_{bio}	Primary energy factors of natural gas, electricity importation and biomass consumption (kWh/kWh)
$q_{PV} q_e, q_{ng}$	Year-round electricity and natural gas consumption of building operation at pre-retrofitting stage (kWh)
$e_{INS}, e_{PV}, e_{WT}, e_{SH}$	Embodied energy of insulation, PV panel, wind turbine and solar heater (kWh)

3.4.2 Life-cycle net-zero carbon (LCNZC)

LCNZC is assessed on the principle that greenhouse gas reduction through adopting the retrofitting resolutions is no less than the total of embodied carbon in the retrofitting materials and building greenhouse gas emissions over NZAY.

$$\text{Carbon emission reduction through retrofitting measures} \times \text{Years for achieing net-zero} > \text{Carbon emissions of buidling operation at pre-retrofitting stage} + \text{Embodied carbon of retrofitting materials} \times \text{Years for achieing net-zero}$$

For PV panel and envelope insulation only,

$$c_{ele}q_{PV}A_{PV} \times NZAY > (c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{PV}A_{PV} + c_{INS}A_{INS}$$

For wind turbine and envelope insulation only,

$$c_{ele}q_{WT}A_{WT} \times NZAY > (c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{WT}A_{WT} + c_{INS}A_{INS}$$

For solar heater and envelope insulation only,

$$c_{ng}q_{SH}A_{SH} \times NZAY > (c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{SH}A_{SH} + c_{INS}A_{INS}$$

For biomass boiler and envelope insulation only,

$$(c_{ng}q_{BB,pr,h} - c_{bio}q_{BB,con})A_{BB} \times NZAY > (c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{BB}A_{BB} + c_{INS}A_{INS}$$

For CHP and envelope insulation only,

$$(c_{ele}q_{CHP,pr,e} + c_{ng}q_{CHP,pr,h} - c_{bio}q_{CHP,con})A_{CHP} \times NZAY > (c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{CHP}A_{CHP} + c_{INS}A_{INS}$$

For integrated adoption of different retrofitting options,

$$[c_{ele}(q_{PV}A_{PV} + q_{WT}A_{WT} + q_{CHP,pr,e}A_{CHP}) + c_{ng}(q_{SH}A_{SH} + q_{CHP,pr,h}A_{CHP} + q_{BB,pr,h}A_{BB}) - c_{bio}(q_{CHP,con} + q_{BB,con})] \times NZAY >$$
$$(c_{ele}q_{e} + c_{ng}q_{ng}) \times NZAY + c_{PV}A_{PV} + c_{WT}A_{WT} + c_{SH}A_{SH} + c_{CHP}A_{CHP} + c_{BB}A_{BB} + c_{INS}A_{INS}$$

where,

c_{ng}, c_{ele}, c_{bio}	Embodied carbon factors of natural gas, electricity importation and biomass consumption (kWh/kWh)
$c_{en}, c_{PV}, c_{WT}, c_{SH}$	Embodied carbon of insulation, PV panel, wind turbine and solar heater (kWh)

3.3 Retrofitting evaluation criteria

The retrofitting evaluation criteria include payback period of embodied energy Y_e, investment cost Y_{co} and embodied carbon Y_c of retrofitting measures, which indicates the length of time when the embodied energy, investment cost, and embodied carbon can be paid back through reduction on economic cost, energy use, and greenhouse gas emissions. It is assumed that there is no degradation of the renewable energy devices. In other words, the efficiency of PV panel, solar heater, wind turbine, biomass CHP system and biomass boiler is constant during its life span.

$$Y_e = \left(e_{PV,r}A_{PV} + e_{SH,r}A_{SH} + e_{WT,r}A_{WT} + e_{CHP,r}A_{CHP} + e_{BB,r}A_{BB}\right)/(e_{ele}q_{PV}A_{PV} + e_{ele}q_{WT}A_{WT} + e_{ng}q_{SH}A_{SH} + e_{ele}q_{CHP,pr,e}C_{CHP} + e_{ng}q_{CHP,pr,h}C_{CHP} + e_{ng}q_{BB,pr,h}C_{BB} - e_{bio}q_{BB,co}A_{BB} - e_{bio}q_{CHP,co}C_{CHP}) \quad (2)$$

$$Y_{co} = \left(co_{PV,r}A_{PV} + co_{SH,r}A_{SH} + co_{WT,r}A_{WT} + co_{CHP,r}A_{CHP} + co_{BB,r}A_{BB}\right)/(co_{ele}q_{PV}A_{PV} + co_{ele}q_{WT}A_{WT} + co_{ng}q_{SH}A_{SH} + co_{ele}q_{CHP,pr,e}A_{CHP} + co_{ng}q_{CHP,pr,h}C_{CHP} + co_{ng}q_{BB,pr,h}C_{BB} - co_{bio}q_{BB,con}A_{BB} - co_{bio}q_{CHP,con}A_{CHP}) \quad (3)$$

$$Y_c = \left(c_{PV,r}A_{PV} + c_{SH,r}A_{SH} + c_{WT,r}A_{WT} + c_{CHP,r}A_{CHP} + c_{BB,r}A_{BB}\right)/(c_{ele}q_{PV}A_{PV} + c_{ele}q_{WT}A_{WT} + c_{gas}q_{SH}A_{SH} + c_{ele}q_{CHP,pr,e}C_{CHP} + c_{ng}q_{CHP,pr,h}C_{CHP} + c_{ng}q_{BB,pr,h}C_{BB} - c_{bio}q_{BB,co}A_{BB} - c_{bio}q_{CHP,co}C_{CHP}) \quad (4)$$

$e_{i,r}$ and $c_{i,r}$ refers to the recurrent embodied energy and embodied carbon, respectively. i refers to biomass, natural gas and electricity, respectively. If the service life of a certain retrofitting measure is shorter than the life span (i.e. 50 years), the original investment cost would be multiplied according to its service life.

Lifetime payback energy (LP_e) is defined as the difference between total energy reduction through retrofitting during its life span and the total embodied energy of retrofitting energy devices. Lifetime payback carbon (LP_c) is defined as the difference between total carbon reduction through retrofitting during its life span and the total embodied carbon of retrofitting energy devices.

$$LP_e = (e_{ele}q_{PV}A_{PV} + e_{ele}q_{WT}A_{WT} + e_{ng}q_{SH}A_{SH} + e_{ele}q_{CHP,pr,e}A_{CHP} + e_{ng}q_{CHP,pr,h}A_{CHP} + e_{ng}q_{BB,pr,h}A_{BB} - e_{bio}q_{BB,con}A_{BB} - e_{bio}q_{CHP,con}A_{CHP}) \cdot LS - \left(e_{PV,r}A_{PV} + e_{SH,r}A_{SH} + e_{WT,r}A_{WT} + e_{CHP,r}A_{CHP} + e_{BB,r}A_{BB}\right) \quad (5)$$

$$LP_c = (c_{ele}q_{PV}A_{PV} + c_{ele}q_{WT}A_{WT} + c_{ng}q_{SH}A_{SH} + c_{ele}q_{CHP,pr,e}A_{CHP} + c_{ng}q_{CHP,pr,h}A_{CHP} + c_{ng}q_{BB,pr,h}A_{BB} - c_{bio}q_{BB,con}A_{BB} - c_{bio}q_{CHP,con}A_{CHP}) \cdot LS - \left(c_{PV,r}A_{PV} + c_{SH,r}A_{SH} + c_{WT,r}A_{WT} + c_{CHP,r}A_{CHP} + c_{BB,r}A_{BB}\right) \quad (6)$$

The lifetime total cost of the building during the post-retrofitting stage is defined as:

$$COST_{total} = \left(e_{ele}\, q_e + e_{ng}\, q_g\right) \cdot LS + co_{INS} - LP_{co} \tag{7}$$

3.4 Implementation of case study

In order to demonstrate the performance of the proposed integerated design process, it is implemented on a real-life case study building. The detailed information regarding the case study building is summarised in Section 4. Five cases are introduced to illustrate different retrofitting situations. Case 1 indicates that the 1st option can be fully adopted. Case 2 means that the 1st option is 50% partially limited, while the 2nd option can be fully applied. Case 3 indicates that the 1st and 2nd options are 50% partially limited, while the 3rd option can be fully applied. Case 4 indicates that the 1st, 2nd and 3rd options are 50% partially limited, while the 4th option can be fully applied. Case 5 indicates that the 1st, 2nd, 3rd and 4th options are 50% partially limited, while the 5th option can be fully applied.

4 Real-world case study

To evaluate the feasibility of building retrofitting towards LCNZE and LCNZC, a real-world office building is used in the case study. Basic building information, historical weather data, historical energy consumption profile, and life-cycle inventory information are adopted to evaluate the retrofitting measures for transforming the existing high-rise office building into LCNZE or LCNZC.

4.1 Basic building information

The case study is implemented on a real-world high-rise building Costain House is located in Manchester, the United Kingdom. It is a typical three-floor medium-sized modern office building block, which consists of multiple small office rooms and conference rooms. The front view of the case study building is shown in Fig. 2. Its floor area, external wall area and window area are 1428 m^2, 697 m^2 and 1331 m^2, respectively. Heating is provided using traditional gas boiler with built-in air conditioning with a thermal efficiency of 80%. Lighting is provided by the combination of LED and strip fluorescent lighting. Natural lighting can be fully utilised through large glazing areas. The scheduled number of occupancy is 80 per floor, while the fresh air requirement is 10L/s/person. The U-value of the original external wall and roof is 2.45 $W/m^2{\cdot}K$. The building is installed with double-glazing window with the U-value of 1.69 $W/m^2{\cdot}K$. Based on our previous study, envelope insulation has a relatively low investment cost and fair energy-saving performance [34, 35]. When the roof is covered by sheep wool with a thickness of 0.15 m, while the entire external wall is attached with an insulation board with a thickness of 0.7 m, their U-value can be reduced to 0.251 $W/m^2{\cdot}K$ and 0.256 $W/m^2{\cdot}K$, respectively. Therefore, both roof and external wall insulation is adopted as fundamental retrofitting options.

Fig. 2. Front-view of Costain House in Manchester.

4.2 Retrofitting options and simulation model

The impacts of retrofitting measures on operational energy of the building is assessed through fundemantal thermodynamic and first principle equations. Energy transfer through thermal transmission, ventilation, infiltration and solar radiation is calculated using the governing equations of heat conduction [36]. Meanwhile, thermodynamic models of PV panel [37], biomass boiler [38], cogeneration system [39], solar heater [40] and performance curve of wind turbine [41] are applied to estimate the yearly thermal and electrical energy production while exploring the corresponding carbon reduction capability. The design specifications of each energy device are summarised in Table 2, while their thermodynamic models are summarised in Table 3.

Table 2. Parameters of different retrofitting options.

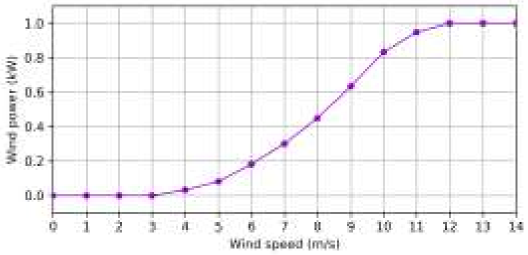
PV panel [41]	Rated efficiency $\eta_{PV,n}$ (%)	12
	Reference temperature $T_{PV,ref}$ (K)	298
	Reference radiation $G_{PV,ref}$ (W m^2)	1000
	Temperature correction coefficient ε_T	-0.005
	Radiation correction coefficient ε_φ	0.000025
Solar heater [42]	Rated efficiency $\eta_{SH,n}$ (%)	44
Wind turbine [43]	Performance map	
Biomass CHP system [44]	Electrical efficiency $\eta_{CHP,e}$ (%)	18
	Thermal efficiency $\eta_{CHP,h}$ (%)	72
Biomass boiler [45]	Efficiency η_{BB} (%)	92

Table 3. Thermodynamic model of each retrofitting option.

First principle of building thermal model [36]	$Q_{trans} = U_{wall}A_{wall}CLTD_{wall} + U_{win}A_{win}CLTD_{win} + U_{roof}A_{roof}CLTD_{roof}$ $Q_{vent} = \rho_a C_{p,a} v_{vent}(T_{oa} - T_{ia})$ $Q_{inf} = \rho_a V C_{p,a} ACH(T_{oa} - T_{ia})$ $Q_{solar} = SHGF \cdot G \cdot (SC \cdot A_{win} + A_{roof})$
PV panel [37]	$Q_{PV} = G \cdot S_{PV} \cdot \eta_{PV}$ $\eta_{PV} = \eta_{PV,n}[1 + \varepsilon_T(T_{db} - T_{PV,ref})][1 + \varepsilon_\varphi(G - G_{PV,ref})]$
Solar heater [38]	$Q_{SH} = G \cdot A_{SH} \cdot \eta_{SH}$ $\eta_{SH} = \eta_{SH,n} - \alpha \times (T_{DB} - T_{SH,ref})/G$
CHP system [39]	$q_{CHP,e} = q_{CHP,co}\eta_{CHP,e}$ $q_{CHP,h} = q_{CHP,co}\eta_{CHP,h}$
Biomass boiler [40]	$q_{BB,pr,h} = q_{BB,co}\eta_{BB}$

4.3 Historical weather profile

The historical weather profile recorded at Manchester in the year 2019 is adopted as inputs to those first principle thermodynamic models. The historical weather data mainly consists of dew-point temperature, outdoor temperature, wind speed, cloud cover percentage and solar radiation, as summarised in Fig. 3. The maximum wind speed is 12 m/s while the highest solar radiation is 900 W/m^2.

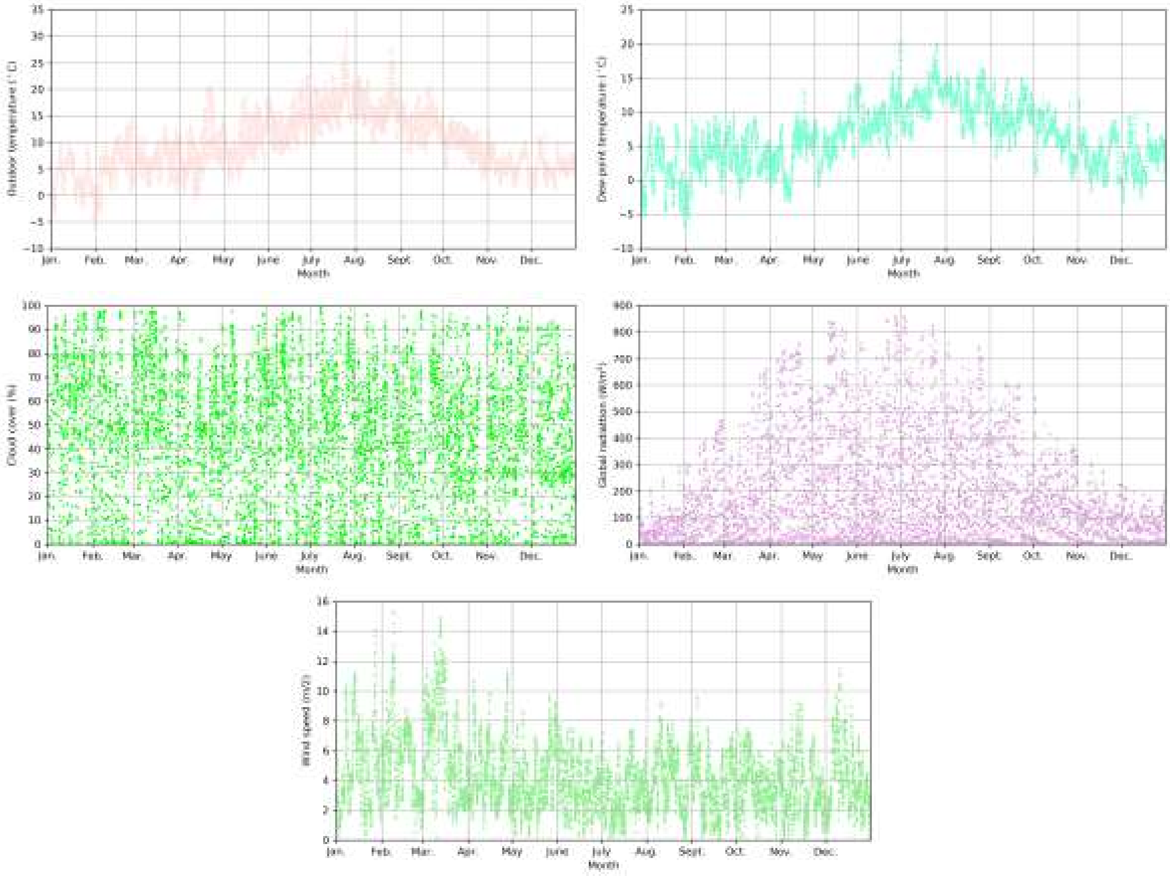
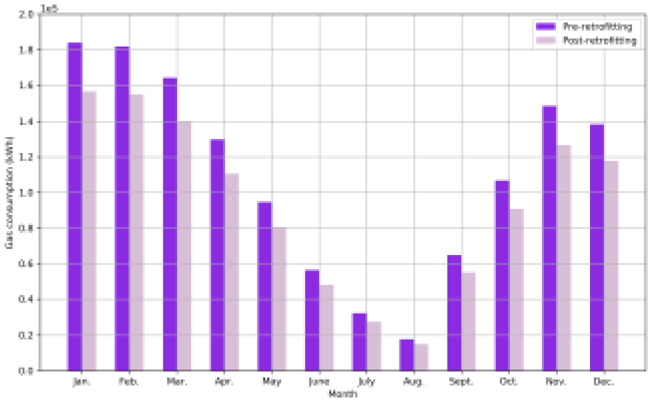


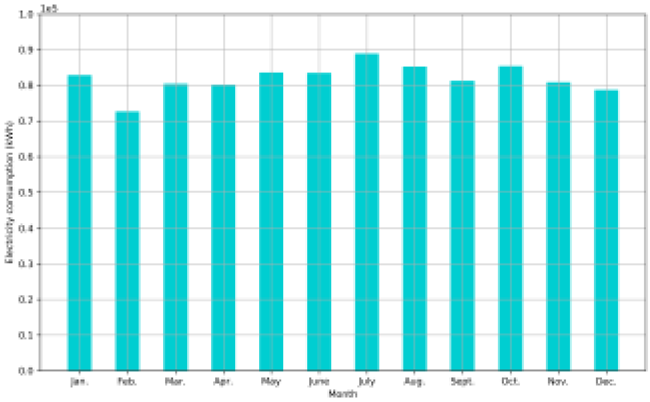
Fig. 3. Outdoor weather profile.

4.4 Building energy performance

The consumption rate of natural gas and electricity at the pre-retrofitting stage can be estimated from the energy bill, which was 308 kWh/m^2 and 230 kWh/m^2 in 2019, respectively. The large window-to-wall ratio (i.e. 2) leads to the large heat load and high consumption rate of natural gas, while the continuously working high-rise computing servers result in a high consumption rate of electricity. The natural gas consumption at post-retrofitting stage is estimated using thermal building models described in Table 3. There would be approximately 15% natural gas reduction owing to the reduced heat loss by installing roof and wall insulation. The peak natural gas consumption happens in January and February due to the low dry-bulb and dew-point temperature of outdoor air. The peak electricity is identified in July, while the valley happens in February. Fig. 3 is adopted to describe the year-round consumption rate of natural gas and electricity. The natural gas and electricity demand at the post-retrofitting stage refers to q_g and q_e in Eqs. 1-9.



(a) Gas



(b) Electricity

Fig. 3. Monthly gas and electricity consumption.

4.5 Generated renewable energy from renewable energy devices

The electrical energy generated from PV panel and wind turbine, along with thermal energy produced by solar heater can be estimated through thermodynamic models in Table 3. The yearly renewable energy production is summarised in Table 4. The electrical energy production generated by PV panel and wind turbine, as well as the thermal energy production from solar heater refers to q_{PV}, q_{WT} and q_{SH} in Eqs. 1-9.

Table 4. Peak and yearly renewable energy production.

Energy device	Design area or rated power	Peak (kW)	Yearly production (kWh)
PV panel	1 m^2	0.106	121.8
Wind turbine	1 kW	1	1217.0
Solar heater	1 m^2	0.674	765.6

4.6 Inventory data

As introduced in Section 2, the embodied energy refers to primary energy use while embodied carbon indicates greenhouse gas emissions during the production stage (A1-A3) and end-of-life stage (C1-C4) minus reuse-recovery-recycling potential outside the system boundary (D). Table 4 summarises the inventory economic, energy and environmental information collected from various sites in the UK.

Table 5. Summary of inventory data.

Energy or energy devices	Unit	Economic cost (£)	Embodied energy (MJ)	Embodied carbon ($kgCO_2e$)
Electricity from power grid [46, 47]	kWh	0.1310	9.0	0.21233
Biomass [46, 48]	kWh	0.0126	0.455	0.01513
Natural gas [46, 49]	kWh	0.0211	3.6	0.18316
Sheep wool [50-52]	m^2	18.67	97.65	44.31
Insulation board [50-52]	m^2	24.5	70.0	3.43
PV panel [53-55]	m^2	219	3266.6	157.8
Wind turbine [56, 57]	kW	83050	555666.7	3487.7
Solar heater [58, 59]	m^2	38	3000	240

CHP system [60]	kW	1750	138800	5920
Biomass boiler [61]	kW	90.4	57005.2	471

5 **Results and discussion**

First of all, a life-cycle assessment of each renewable energy device is conducted, with the analysis of payback time of embodied energy, investment cost and embodied carbon. Secondly, the design area and rated power of each renewable energy device in achieving LCNZE and LCNZC building are analysed. Moreover, the picking order and combination of different retrofitting options in achieving net-zero building are analysed, along with the associated embodied energy, investment cost and embodied carbon. In addition, each resolution is evaluated using life cycle criteria.

5.1 Life cycle assessment of renewable energy devices

The payback year of embodied energy, investment cost and embodied carbon of each energy device is summarised in Table 5.

- Biomass boiler has the shortest payback time of investment cost, afterwards biomass CHP system, solar heater, wind turbine and PV panel.
- Solar heater also has the shortest payback time of embodied energy, afterwards biomass CHP system, biomass boiler, PV panel and wind turbine.
- Biomass boiler has the shortest payback time of embodied carbon, afterwards biomass CHP system, solar heater, PV panel and wind turbine.
- For each renewable energy device, the payback year of embodied energy and payback year of embodied carbon is generally shorter than the payback year of investment cost.

Table 6. Payback year of embodied energy, investment cost and embodied carbon of different devices.

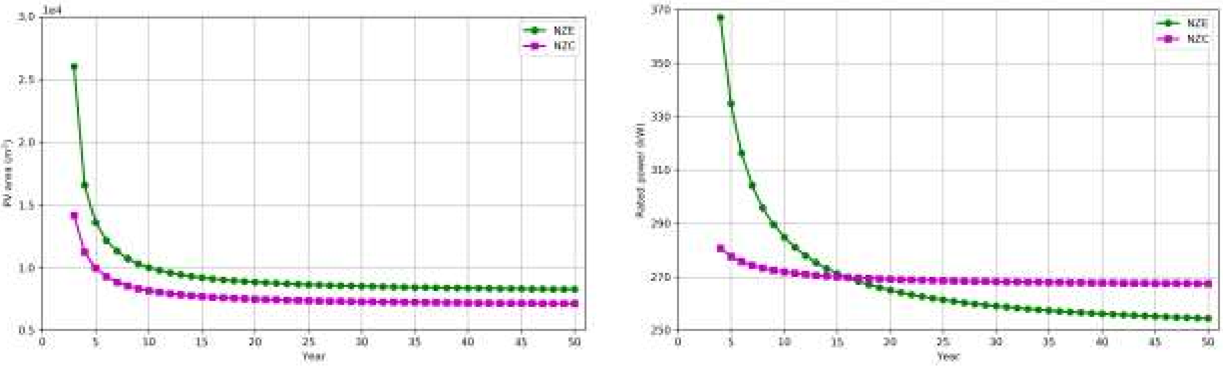
Retrofitting devices	Energy	Cost	Carbon

Biomass boiler	1.30	0.42	0.20
PV panel	2.09	12.38	1.54
Solar heater	0.50	1.12	0.77
CHP system	0.68	1.03	0.49
Wind turbine	5.29	11.31	9.66

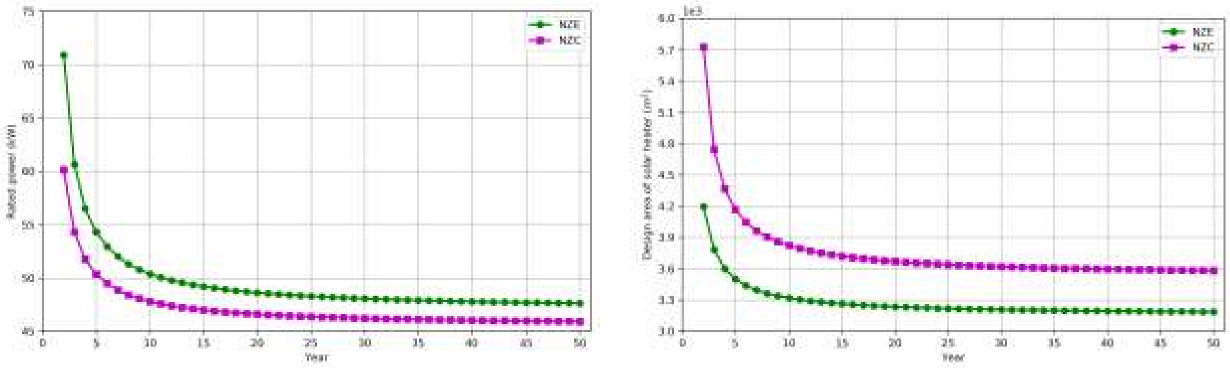
5.2 Performance evaluation of adopting single retrofitting measures for LCNZE and LCNZC

The required design area and rated power of single adoption of each renewable energy device for achieving LCNZE and LCNZC in different NZAY are summarised in Fig. 4. The needed design area and rated power decreases with the increase of NZAY, while it reaches relatively steady after 30, 40, 35, 35 and 30 years, respectively, for PV panel, biomass boiler, biomass CHP system, solar heater and wind turbine. For PV panel, CHP system, solar heater, and wind turbine, the design area and rated power for achieving LCNZE are higher than those for LCNZC.

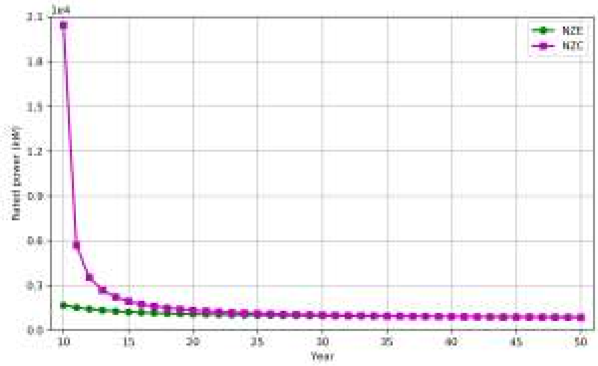
- For achieving LCNZE in 20 years, the required design area and rated power of PV panel, biomass boiler, biomass CHP system, solar heater and wind turbine are 9000 m^2, 267 kW, 49 kW, 3250 m^2, and 1400 kW, respectively.
- For achieving LCNZC in 20 years, the required design area and rated power of PV panel, biomass boiler, biomass CHP system, solar heater and wind turbine are 7500 m^2, 270 kW, 47 kW, 3650 m^2, and 1500 kW, respectively.



(a) PV panel (b) Biomass boiler



(c) CHP system (d) Solar heater



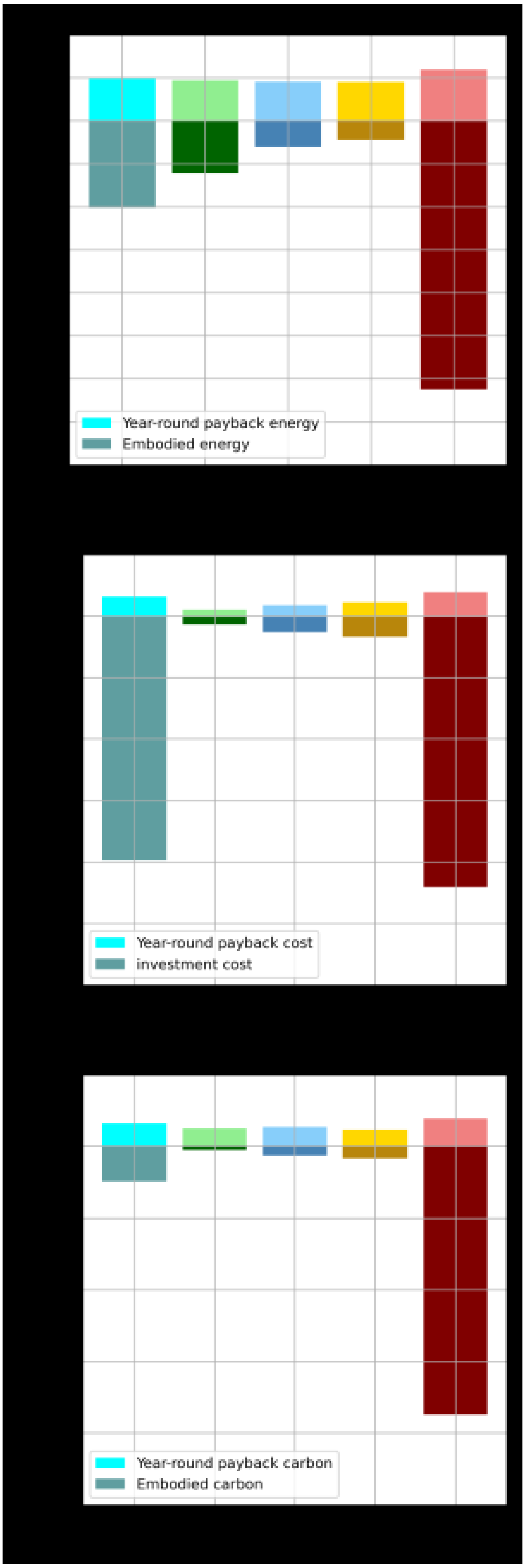
(e) Wind turbine

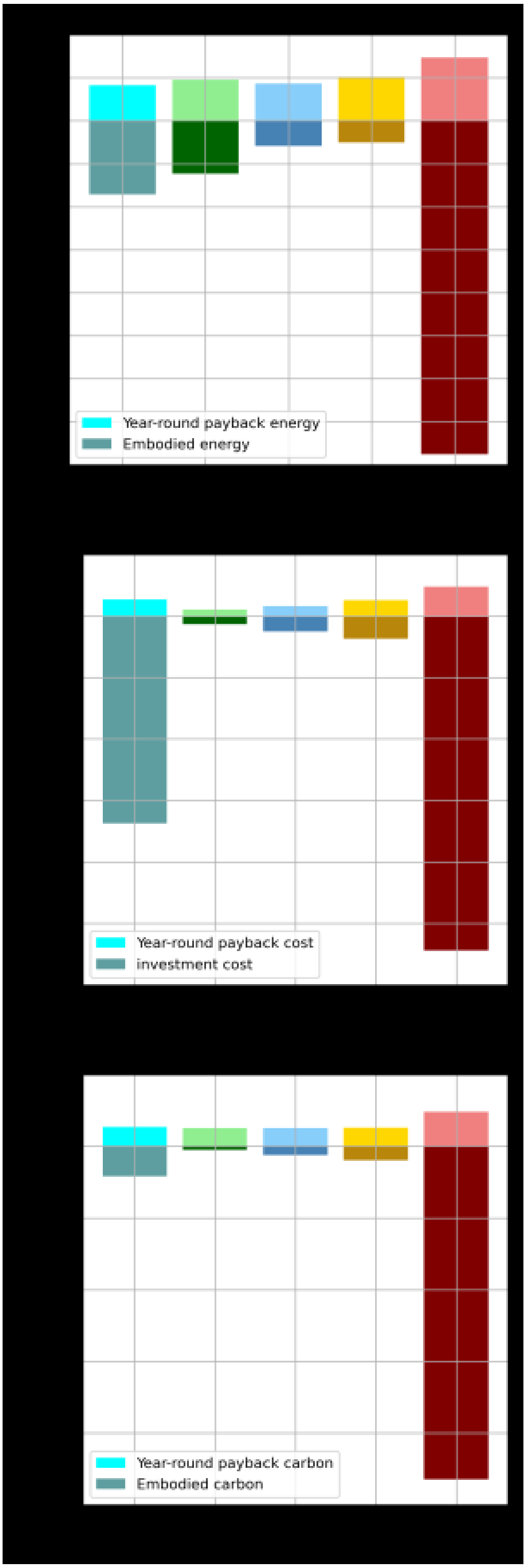
Fig. 4. The design area or power for achieving LCNZE and LCNZC of each retrofitting option.

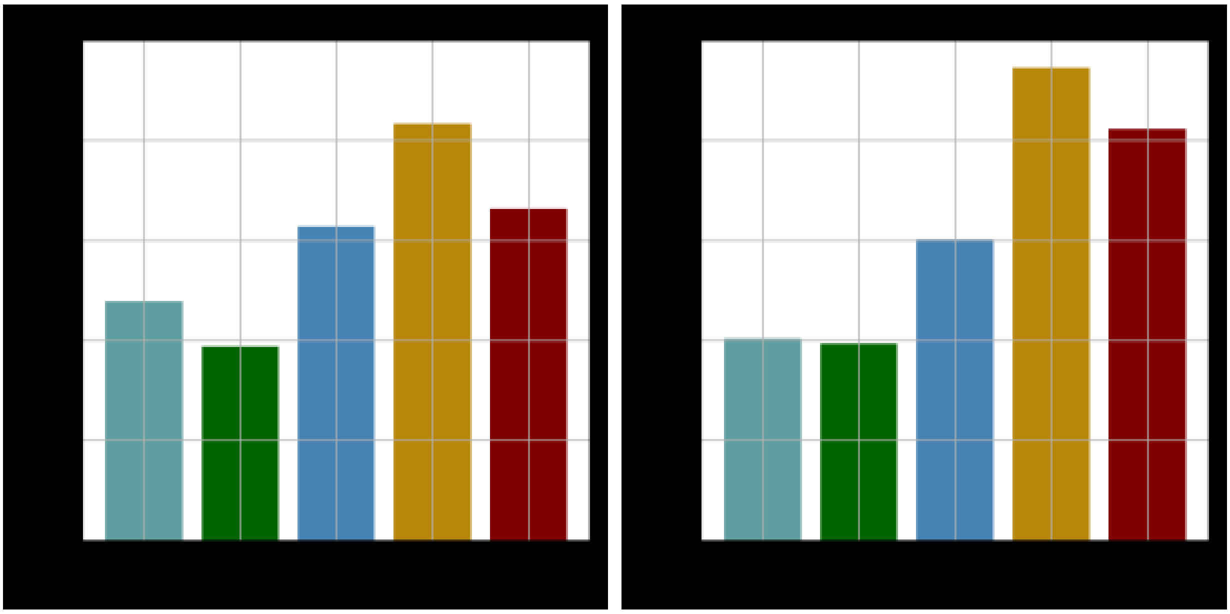
When the NZAY for LCNZE and LCNZC is set at 20, the embodied energy, investment cost and embodied carbon, along with the year-round payback cost, energy and carbon from single application different renewable energy devices are summarised in Fig. 5, along with the lifetime payback cost of each renewable energy device.

- For achieving either LCNZE or LCNZC, wind turbine has the highest year-round payback cost, afterwards PV panel, solar heater, biomass CHP system and biomass boiler. On the other hand, wind turbine has the highest investment cost, afterwards PV panel, solar heater, biomass CHP system and biomass boiler.
- For achieving LCNZE, wind turbine has the highest year-round payback energy, afterwards PV panel, biomass boiler, biomass CHP system and solar heater. The embodied energy of renewable energy devices almost follows the same trend as the year-round payback energy.
- For achieving LCNZC, wind turbine has the highest year-round payback energy, afterwards solar heater, biomass boiler, biomass CHP system and PV panel. Moreover, wind turbine has the highest embodied energy, afterwards PV panel, biomass boiler, biomass CHP system and solar heater.
- For achieving LCNZE, wind turbine has the highest year-round payback carbon, afterwards PV panel, CHP system, biomass boiler and solar heater. On the other hand, wind turbine has the highest embodied carbon, afterwards PV panel, solar heater, biomass CHP system and biomass boiler.
- For achieving LCNZC, wind turbine has the highest year-round payback carbon, afterwards PV panel, solar heater, CHP system and biomass boiler. Meanwhile, wind turbine has the highest embodied carbon, afterwards PV panel, solar heater, biomass CHP system and biomass boiler.
- For achieving either LCNZE or LCNZC, solar heater has the highest lifetime payback cost, afterwards wind turbine, biomass CHP system, PV panel and biomass boiler.

As it can be seen, higher year-round payback cost does not necessarily mean higher lifetime payback cost. For example, annual payback cost of wind turbine is higher than that of solar heater. On the contrary, lifetime payback cost of solar heater is larger than that of wind turbine. It is because that the investment cost of wind turbine is higher than that of the solar heater.


Year-round payback energy
Embodied energy
Year-round payback cost
investment cost
Year-round payback carbon
Embodied carbon


Year-round payback energy
Embodied energy
Year-round payback cost
investment cost
Year-round payback carbon
Embodied carbon



(a) LCNZE (b) LCNZC

Fig. 5. Investment, year-round payback and lifetime payback of different renewable energy devices.

The lifetime total cost of each renewable energy device for achieving LCNZE or LCNZC is demonstrated in Table 7. With the adoption of roof and wall envelop, there would be a 12% decrease of lifetime total cost compared to pre-retrofitting. For achieving LCNZE, solar heater results in a negative lifetime total cost. For achieving LCNZC, solar heater and wind turbine result in the negative lifetime total cost. It indicates that the equivalent revenue earned from renewable energy production is higher than the total investment cost of retrofitting measures and total electricity cost of the building. For either achieving LCNZE or LCNZC, solar heater results in the highest cost-saving ratio (i.e. over 100%). Biomass boiler has the lowest cost-saving ratio, which is around 53%.

Table 7. Lifetime total cost (£).

PV panel		Biomass boiler		CHP system		Solar heater		Wind turbine		Envelope only	Pre-retrofitting
LCNZE	LCNZC	LCNZE	LCNZC	LCNZE	LCNZC	LCNZE	LCNZC	LCNZE	LCNZC		
810603	995205	1036974	1021912	435251	500761	-76290	-356053	347414	-50820	2005612	2186986
63%	54%	53%	53%	80%	77%	103%	116%	84%	102%	8%	0%

4.3 Integrated retrofitting resolution in achieving LCNZE/LCNZC

As shown in Table 7, solar heater has the highest lifetime payback cost, afterwards wind turbine, biomass CHP system, PV panel and biomass boiler. Therefore, solar heater would be primarily selected as the retrofitting choice. As shown in Fig. 6, the design area of solar heater should be 3235 m^2 for achieving LCNZE. If the maximum allowable area for solar heater is smaller than 3235 m^2, wind turbine would be installed as it has the second-highest lifetime payback cost. And so on so forth for CHP system, PV panel and biomass boiler.

In the following study, Case 1 indicates that the 1st option (i.e. solar heater) can be fully adopted. Case 2 means that the 1st option is 50% partially limited, while the 2nd option (i.e. wind turbine) can be fully applied. Case 3 indicates that the 1st and 2nd options are 50% partially limited, while the 3rd option (i.e. CHP system) can be fully applied. Case 4 indicates that the 1st, 2nd and 3rd options are 50% partially limited, while the 4th option (i.e. PV panel) can be fully applied. Case 5 indicates that the 1st, 2nd, 3rd and 4th options are 50% partially limited, while the 5th option (i.e. biomass boiler) can be fully applied. The portation of embodied energy, investment cost and embodied carbon of each renewable energy device is summarised in Fig. 6 for retrofitting towards LCNZE and LCNZC with the aim of optimal lifetime payback cost. Although wind turbine has the second-highest lifetime payback cost, it occupies a large portion of investment cost, embodied energy and embodied carbon, as demonstrated in Case 2. The lifetime payback revenue, payback year and inventory information of each case is summarised in Fig. 7.

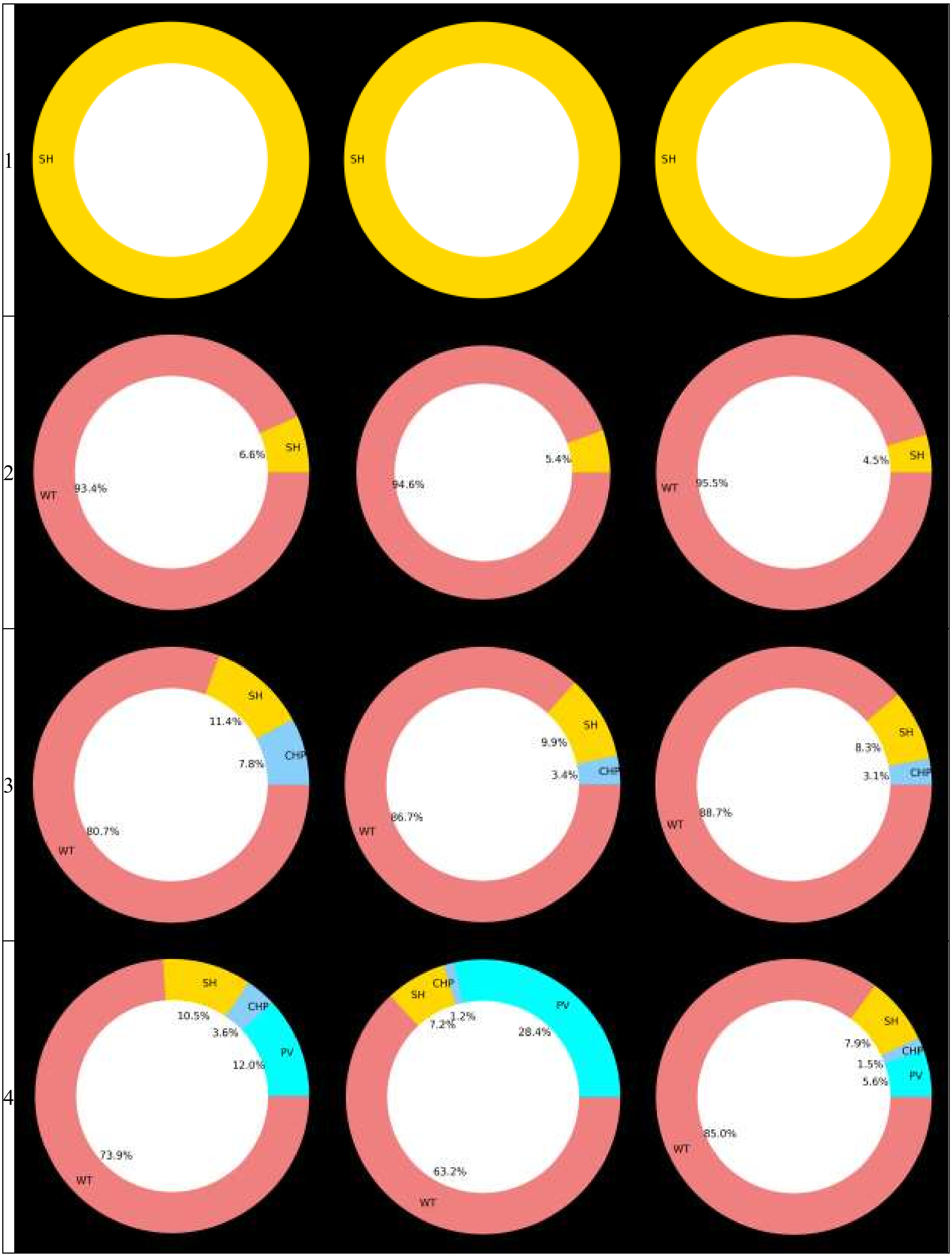
- Case 1 has the largest lifetime payback cost for both LCNZE and LCNZC, afterwards Case 2, Case 3, Case 4 and Case 5. This demonstrates that the optimal lifetime payback cost does achieve in each case. The reduction in lifetime payback cost is due to the limited allowable design area and rated power of the best retrofitting options. On the other hand, Case 2 has the largest lifetime payback energy. It is because that wind turbine for LCNZE/LCNZC results in the highest year-round payback of energy. However, lifetime payback carbon is similar among different cases. In general, LCNZC buildings has higher lifetime payback energy, cost and carbon than those of LCNZE buildings in each case. It is because that the required area of solar heater is higher in LCNZC buildings.

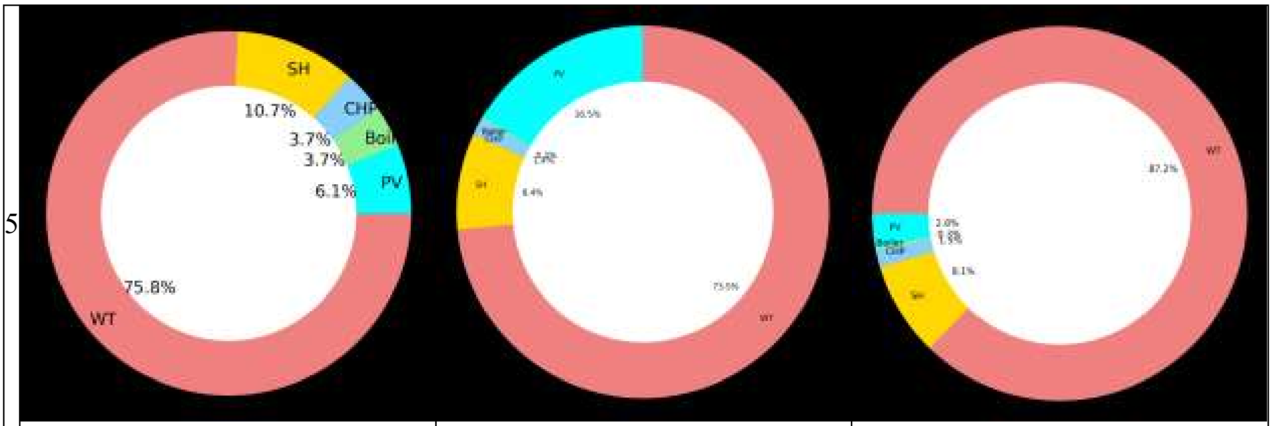
- Case 1 has the smallest payback time of embodied energy, investment cost, and embodied carbon for both LCNZE and LCNZC buildings. However, Case 2 results in the largest payback year, it is mainly due to the large rated power and long payback year of wind turbine.
- Case 1 has the smallest embodied energy, investment cost and embodied carbon for both LCNZE and LCNZC buildings. However, Case 2 results in the largest embodied energy, investment cost and embodied carbon, mainly due to the large rated power and inventory value of wind turbine.

Table 8 summarises the lifetime total cost and cost reduction ratio compared to pre-retrofitting of each retrofitting solution. The negative lifetime total costs indicate that the payback cost from installing renewable energy devices is higher than the operating cost for heating and electricity supply. Therefore, compared to the pre-retrofitting situation, the reduction percentage is higher than 100. The maximum cost reduction would be 116.3% and 103.5% for LCNZE and LCNZC buildings, respectively, while the maximum life-cycle revenue is £356052.7 and £76290.2, respectively. This can be achieved with the investment cost of £122940 and £139196, respectively.

Table 8. Life-time total cost of each retrofitting solution.

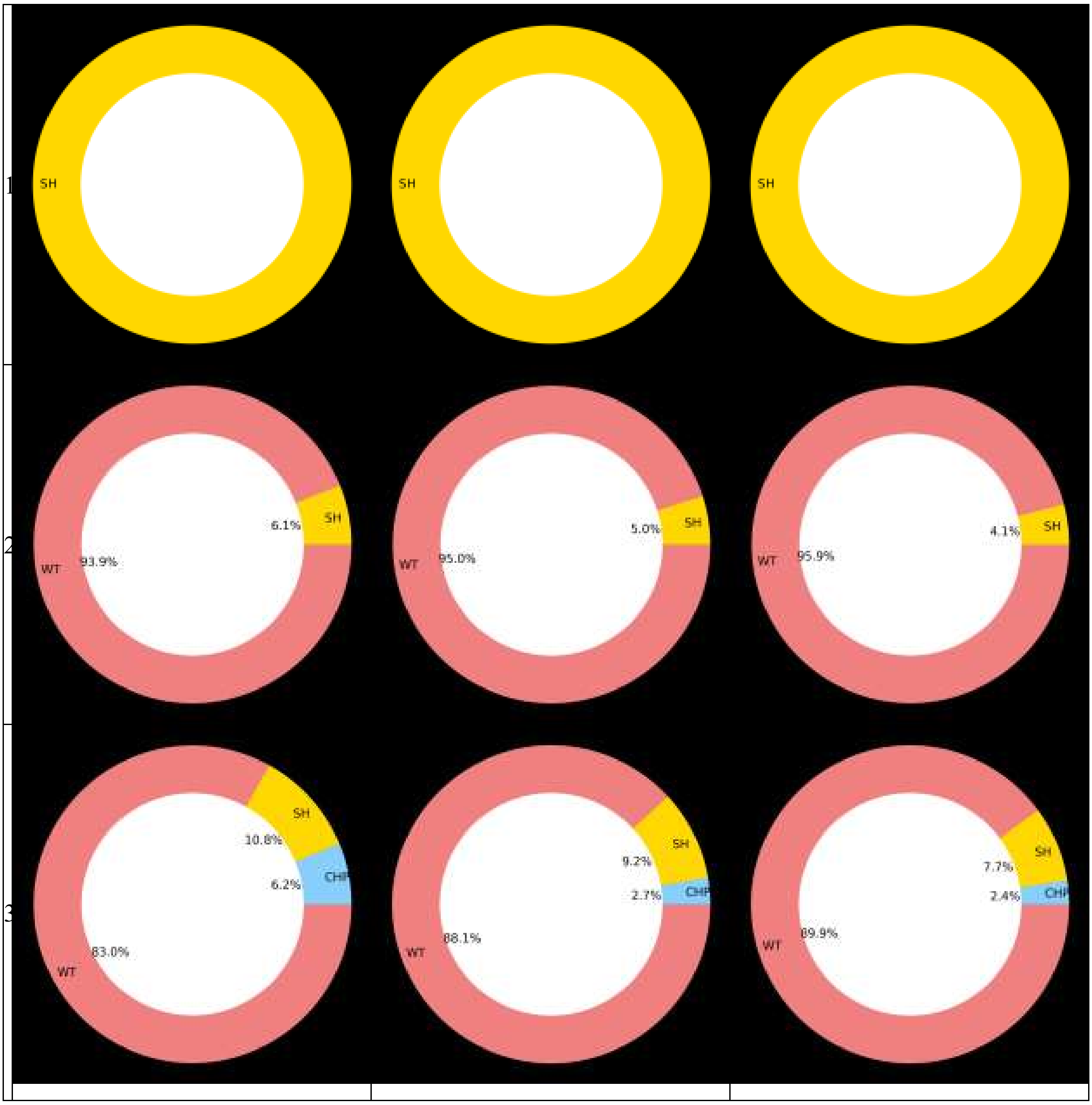
Building	Assessment value	Case 1	Case 2	Case 3	Case 4	Case 5
LCNZE	Lifetime total cost	-356052.7	-203437	-65541.1	-3735.6	-2066.4
	Reduction	116.3%	109.3%	103.0%	100.2%	100.1%
LCNZC	Lifetime total cost	-76290.2	135562	157521	204440	218588
	Reduction	103.5%	93.8%	92.8%	90.7%	90.0%

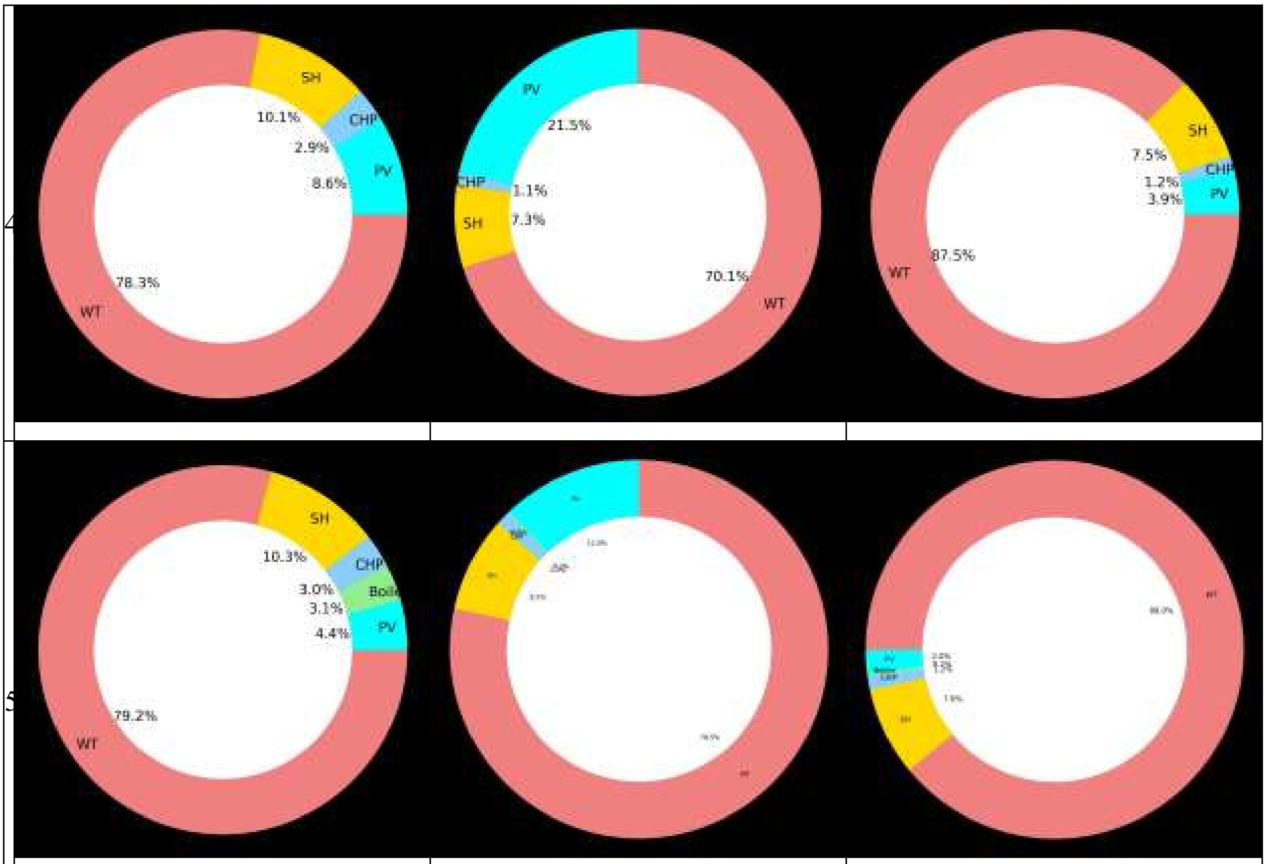

1
SH
SH
SH
2
6.6%
SH
WT
93.4%
5.4%
94.6%
4.5%
SH
WT
95.5%
3
SH
11.4%
CHP
7.8%
80.7%
WT
SH
9.9%
3.4%
CHP
86.7%
WT
SH
8.3%
3.1%
CHP
WT
88.7%
4
SH
CHP
10.5%
3.6%
PV
12.0%
73.9%
WT
CHP
SH
1.2%
7.2%
PV
28.4%
63.2%
WT
SH
7.9%
CHP
1.5%
PV
5.6%
85.0%
WT



Embodied energy | Investment cost | Embodied carbon

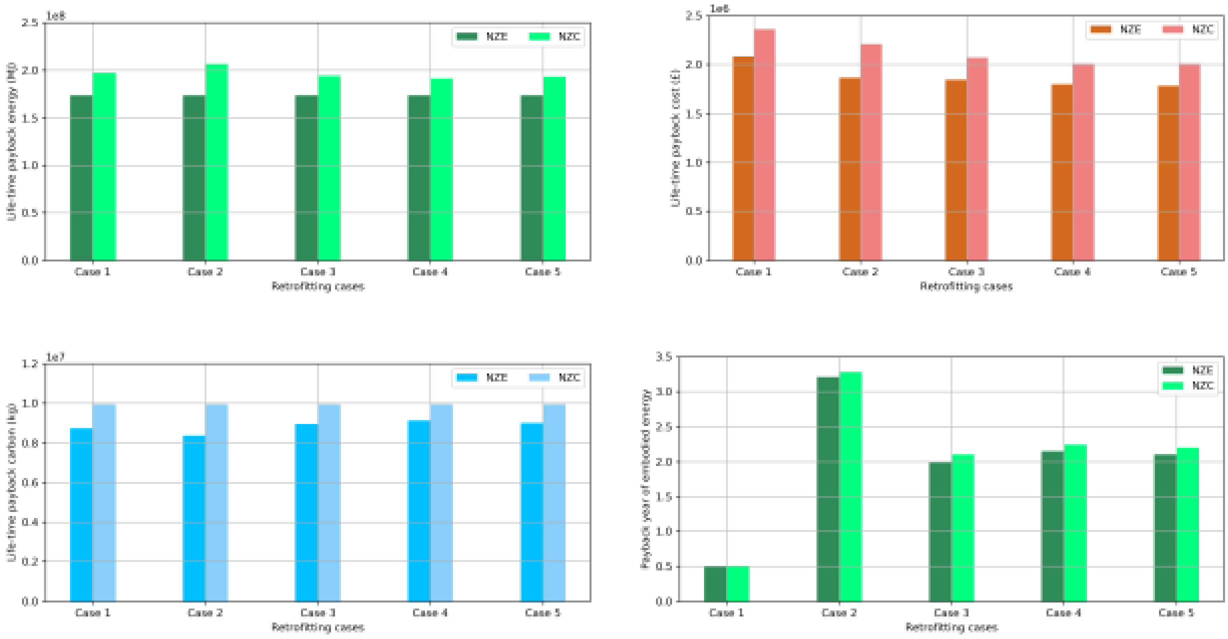
(a) LCNZE.





(b) LCNZC

Fig. 6. Portion of embodied energy and carbon, investment cost for retrofitting LCNZE and LCNZC.



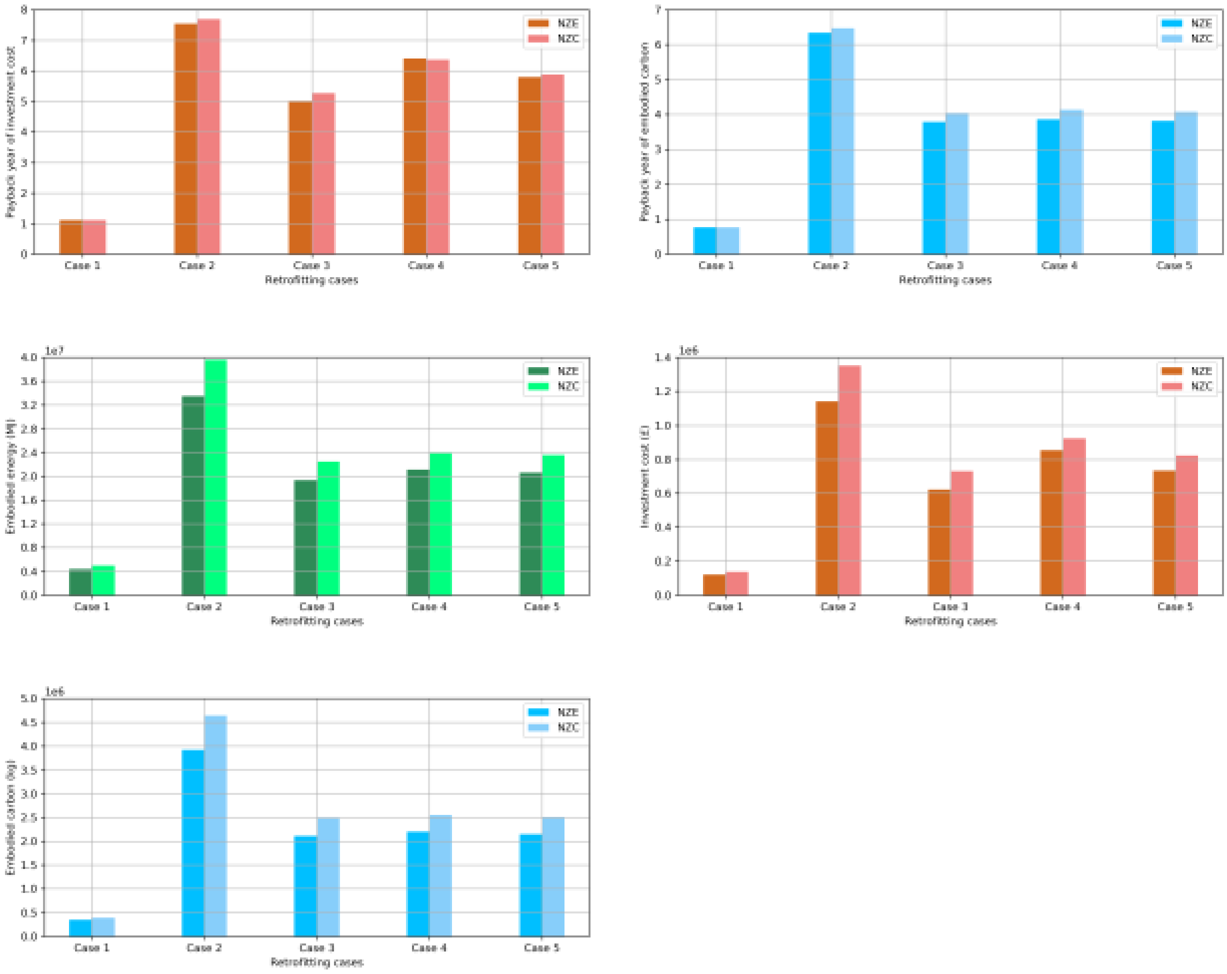


Fig. 7. Lifetime payback revenue, payback year and inventory information of each case.

6 Summary of LCNZE and LCNZC building retrofitting framework in practical implication

The main aim of this study is to propose a retrofitting design approach to transform existing office buildings into life-cycle net-zero energy and carbon, The flow chart in Fig. 8 demonstrates how to use the proposed LCNZE and LCNZC retrofitting design approach in practical implications. At first, past energy bills, inventory information, past weather profile, and basic building information should be collected at the preparation stage. Secondly, lifetime payback energy, cost and carbon, along with payback time of embodied energy, investment cost and embodied carbon of each renewable energy device should be investigated. The life-cycle performance may be affected by the actual building location, mainly due to the unique weather profile and inventory data at different locations. Thirdly, the life-cycle performance of single adoption of renewable energy devices for LCNZE or LCNZC is evaluated, while the picking order of renewable energy devices is determined based on lifetime payback cost. In this studied Manchester building, the picking order is solar heater > wind turbine > CHP system > PV panel > biomass boiler. Finally, the integrated retrofitting design can be formulated based on the relationship between required design area and rated power (i.e. according to LCNZE/LCNZC requirement) and allowed design area and rated power (i.e. according to facility manager).

Following the validation using the real-world case study, the reliability of the proposed LCNZE and LCNZC building retrofitting design approach is demonstrated. Therefore, it can be used as a handful of guidelines for building operators and facility managers to choose their desired retrofitting resolutions as an effort to converting existing high-rise office buildings towards life-cycle net-zero primary energy use and greenhouse gas emissions. Life-cycle net-zero is a stricter definition than conventionally defined operating net-zero. Therefore, the requirement of offset embodied energy and carbon would increase the complexity of the energy balance calculation. By implementing the proposed retrofitting design approach, the building can become truly carbon-neutral at the minimum investment cost. It will significantly contribute to achieving net-zero global ambition.

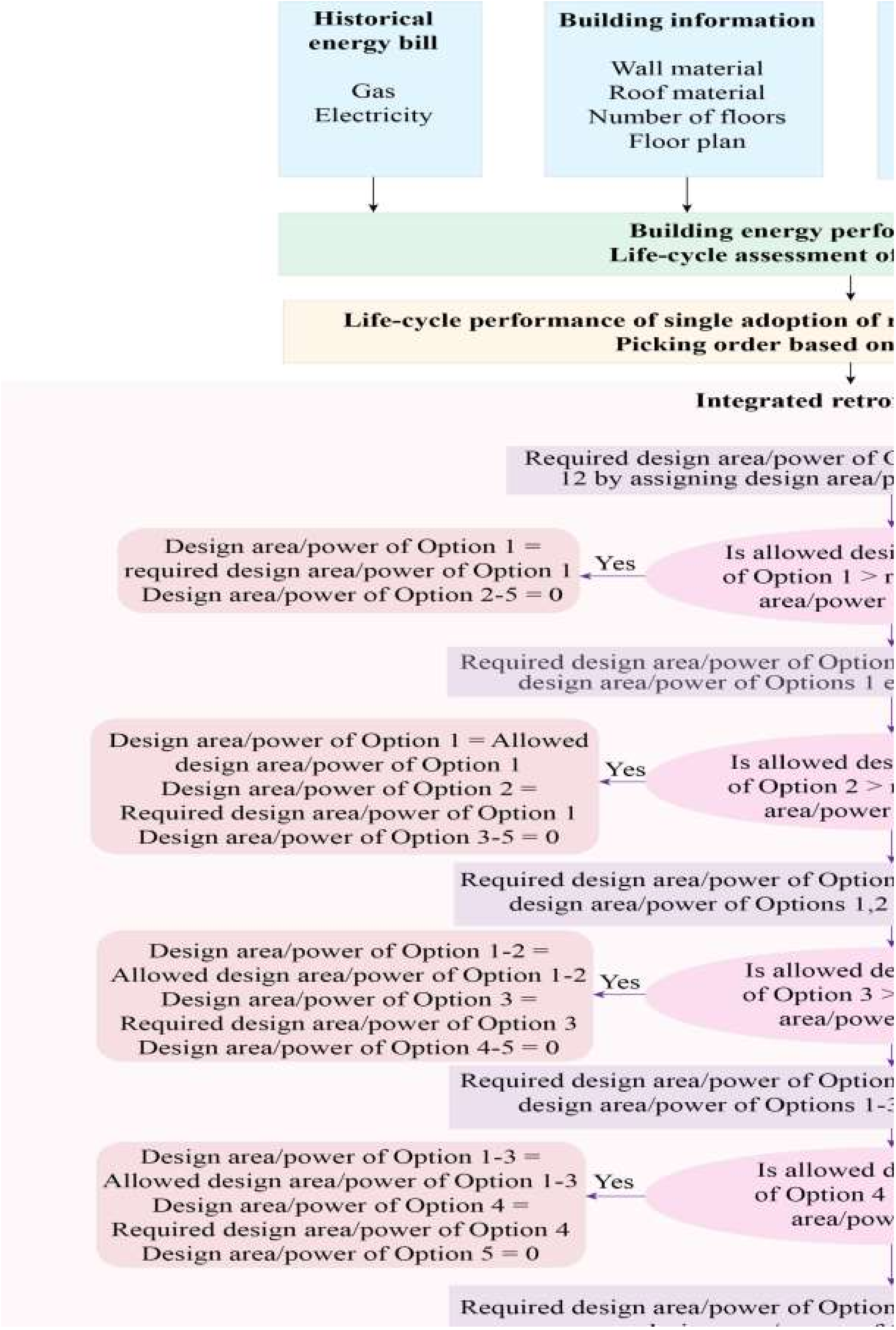


Fig. 8. Framework of building retrofitting towards NCNZE and LCNZC.

7 Limitations and future work

As start-up research and retrofitting design approach of life-cycle net-zero building, there exist several limitations in this study.

First of all, the inventory data for biomass, natural gas and electricity are based on the latest UK statistics. The equivalent primary energy use and greenhouse gas emissions may be different in other countries due to different manufacturing processes of natural gas and electricity. The embodied energy and carbon factors of retrofitting materials are collected from several databases using the processing approach. It is mainly owing to the lack of a completed and updated database for different design and inventory information. The embodied energy and carbon that occurred during the construction process stage is not considered. Therefore, like most life cycle analysis studies, the obtained retrofitting solution may be only applicable to the case study building. It is anticipated that a local inventory database regarding embodied energy and carbon factors of different materials can be developed in order to facilitate the life-cycle assessment of retrofitting materials.

Moreover, the retrofitting measures are limited. The adoption of energy storage, natural ventilation, natural lighting, window shading and operable windows can further reduce energy use and greenhouse gas emissions. The life cycle behaviour of extensive retrofitting measures should be evaluated.

Furthermore, the retrofitting design approach is adopted to select the optimal combination of different retrofitting measures based on their typical design. For example, the length of the solar heater, and the corresponding flow rate of working fluid will have an impact on the outlet temperature of the working fluid and the overall performance of the solar heater. The design specifications of each retrofitting measure can be further optimised.

Despite these limitations, new concepts, guidelines and strategies on achieving life-cycle net-zero energy use and greenhouse gas emissions presented in this study can be implemented in different buildings under different climate conditions. By retrofitting towards LCNZE and LCNZC using the proposed framework, climate change effects can be primarily mitigated; thus, the government's net-zero ambitions can be indeed achieved.

8 Conclusion

Conventional net-zero energy and carbon refer to overall zero primary energy use and greenhouse gas emissions during its operating stage. However, there exist embodied carbon and energy in retrofitting materials and energy devices. Minimising operating carbon emissions and energy consumption may not indicate minimum lifetime payback energy and carbon. To achieve climate neutrality by 2050 in Europe, it is vital to take the entire life cycle energy use and greenhouse gas emissions into account.

The most distinguishing innovation of this study is to explore the feasibility of converting existing office buildings into life-cycle net-zero energy use and greenhouse gas emissions. A novel retrofitting design approach is proposed to identify the optimal retrofitting solution to achieve LCNZE or LCNZC with maximum lifetime payback cost. It is tested on an existing high-rise office building in real life. Therefore, this study has four significant contributions.

- First of all, the life-cycle energy, economic, and environmental performance of different renewable energy devices is evaluated. In view of economy, biomass boiler has the shortest payback time of investment cost, afterwards biomass CHP system, solar heater, wind turbine and PV panel. In view of energy, solar heater has the shortest payback time of embodied energy, afterwards biomass CHP system, biomass boiler, PV panel and wind turbine. In view of environment, biomass boiler has the shortest payback time of embodied carbon, afterwards biomass CHP system, solar heater, PV panel and wind turbine.
- Secondly, the feasibility of transforming an existing office building towards life-cycle net-zero energy consumption and greenhouse gas emissions is investigated with the single adoption of different renewable energy devices. For achieving LCNZE in 20 years, the required design area and rated power of PV panel, biomass boiler, biomass CHP system, solar heater and wind turbine are

9000 m^2, 267 kW, 49 kW, 3250 m^2, and 1400 kW, respectively. It would be 7500 m^2, 270 kW, 47 kW, 3650 m^2, and 1500 kW, respectively, for achieving LCNZC in 20 years. Solar heater results in the highest lifetime total cost saving (i.e. 103%-116%) compared to pre-retrofitting. Biomass boiler results in the lowest cost-saving ratio, which is around 53%.

- Thirdly, a novel framework is devised for transforming the office building towards life-cycle net-zero energy consumption and/or greenhouse gas emissions through the integrated adoption of different retrofitting measures. In this case, the picking order for different energy devices is the solar heater, wind turbine, biomass CHP system, PV panel and biomass boiler.
- Lastly, embodied energy, investment cost, embodied carbon, the payback time of investment cost, the payback time of embodied energy, the payback time of embodied carbon of both LCNZE and LCNZC is evaluated. The maximum life-cycle cost reduction would be 116.3% and 103.5% for LCNZE and LCNZC buildings, respectively. The maximum life-cycle revenue for LCNZE and LCNZC is £356052.7 and £76290.2, respectively, which can be achieved with the investment cost of £122940 and £139196, respectively.

The scope of this study is to propose a retrofitting optimisation approach for transforming the existing buildings into life-cycle net-zero energy or life-cycle net-zero carbon. Although the above conclusions are based upon this specific case study, the proposed feasibility assessment approach and LCNZE/LCNZC retrofitting framework can be easily extended to other office buildings in different climates. The different combination of retrofitting options may be resulted for different types of buildings and for buildings in different climate conditions. Therefore, it can be supplied as a valuable guideline for retrofitting office buildings towards LCNZE and LCNZC. With the adoption of such retrofitting framework on buildings to a large extension, it can truly help achieve net-zero global ambition and mitigate climate change-related problems.

Nomenclature

A	Design area

ACH	Air change per hour
C	Rated power
CE	Carbon emission
$CLTD$	Cooling load temperature differences
COP	Coefficient of performance
COST	Economic cost
C_p	Specific heat
EMB	Embodied
G	Global solar radiation
INV	Investment
L	Life span
LT	Lift-time payback
PEC	Primary energy consumption
q	Year-round energy production or consumption
Q	Heat gain
SC	Shading coefficient
$SHGF$	Solar heat gain factor
T	Temperature
$NZAY$	Net-zero achieving years
U	Heat transfer coefficient
V	Volume of thermal zone
α	Coefficient of solar heater
□	Density
η	Efficiency
ε	Correction coefficient of PV panel

Subscripts

a	Air
C	Carbon
CE	Carbon emission
co	Consumption
E	Energy
ele	Electricity
h	Heat
ia	Indoor air
ng	Natural gas
oa	Outdoor air
PEC	Primary energy consumption
post	Post-retrofitting
ref	Reference

Abbreviations

CHP	Combined heat and power
LCNZC	Life cycle net-zero carbon
LCNZE	Life cycle net-zero energy
PV	Photovoltaic
SH	Solar heater

References

[1] IEA, World Energy Outlook 2019, IEA, Paris, 2019.

[2] Clarke LE, Jiang K, Akimoto K, Babiker M, Blanford GJ, Fisher-Vanden K, Hourcade JC, Krey V, Kriegler E, Loschel A and McCollum D. Assessing Transformation Pathways. In: Climate Change

2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (No. PNNL-SA-102686). Pacific Northwest National Lab.(PNNL), Richland, WA (United States). 2015.

[3] European Parliament and Council, Directive 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. PE/54/2018/REV/1. Off J Eur, L 328, 2018.

[4] European Commission, Building stock characteristics, n.d. https://ec.europa.eu/energy/en/eu-buildings-factsheets-topics-tree/building-stock-characteristics. (last accessed 11 Oct 2021)

[5] European Parliament and Council, Directive 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. PE/4/2018/REV/1. Off J Eur, L 156, 2018.

[6] T Boermans, A John, J Seehusen, F Wehringer, J Groezinger, M Scherberich. Overview of Member States information on LCNZEBs: working version of the Progress Report - Final Report, 2014.

[7] H. Erhorn and H. Erhorn-Kluttig. Overview of national applications of the Nearly Zero-Energy Building (LCNZEB) definition, 2015.

[8] Ferrari S and Beccali M. Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target. J. Sustainable Cities Soc., 32(2017)226-234.

[9]Alkhateeb E and Abu-Hijle B. Potential for retrofitting a federal building in the UAE to net zero electricity building (LCNZEB). Heliyon, 5(2019)01971.

[10]Costa JF, Amorim CND and Silva JCR. Retrofit guidelines towards the achievement of net zero energy buildings for office buildings in Brasilia. J. Build. Eng., 32(2020)101680.

[11]Escandón R, Silvester S and Konstantinou T. Evaluating the environmental adaptability of a nearly zero energy retrofitting strategy designed for Dutch housing stock to a Mediterranean climate. Energy Build., 169(2018)366-378.

[12]Morelli M, Rønby L, Mikkelsen SE, Minzari MG, Kildemoes T and Tommerup HM. Energy retrofitting of a typical old Danish multi-family building to a “nearly-zero” energy building based on experiences from a test apartment. Energy Build., 54(2012)395-406.

[13]Dabaieh M, Makhlouf NN and Hosny OM. Rooftop PV retrofitting: A rehabilitation assessment towards nearly zero energy buildings in remote off-grid vernacular settlements in Egypt. Sol. Energy, 123(2016)160-173.

[14]Huang H, Nazi W, Yu Y and Wang Y. Energy performance of a high-rise residential building retrofitted to passive building standard–A case study. Appl. Therm. Eng., 181(2020)115902.

[15]Aksamija A. Regenerative design and adaptive reuse of existing commercial buildings for net-zero energy use. J. Sustainable Cities Soc., 27(2016)185-195.

[16]Tang F, Chen J, Li J and Rodriguez D. Energy saving actions toward LCNZEBs with multiple-criteria optimisation in current residential buildings. Energy Rep., 6(2020)3008-3022.

[17]Asaee SR, Ugursal VI and Beausoleil-Morrison I. Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings. Energy policy, 126(2019)118-130.

[18]Moran P, O'Connell J and Goggins J. Sustainable energy efficiency retrofits as residential buildings move towards nearly zero energy building (LCNZEB) standards. Energy Build., 211 (2020)109816.

[19]Sun X, Gou Z and Lau SSY. Cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climate: Case study of a zero energy building. J. Cleaner Prod. 183(2018)35-45.

[20]Rabani M, Madessa HB and Nord N. Achieving zero-energy building performance with thermal and visual comfort enhancement through optimisation of fenestration, envelope, shading device, and energy supply system. Sustainable Energy Technol. Assess., 44(2021)101020.

[21]Shea RP, Worsham MO, Chiasson AD, Kissock JK and McCall BJ. A life-cycle cost analysis of transitioning to a fully-electrified, renewably powered, and carbon-neutral campus at the University of Dayton. Sustainable Energy Technol. Assess., 37(2020)100576.

[22]NIBS. A common definition for zero energy buildings. Office of Energy Efficiency & Renewable Energy, The U.S. Department of Energy, Washington, DC. 2015.

[23]Thiel CL, Campion N, Landis AE, Jones AK, Schaefer LA and Bilec MM. A materials life cycle assessment of a net-zero energy building. Energies, 6(2013)1125-1141.

[24]Satola D, Balouktsi M, Lützkendorf T, Wiberg AH and Gustavsen A. How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72. Build. Environ., 192(2021)107619.

[25]UKGBC. Net Zero Carbon Buildings: A Framework Definition. Retrieved from London: https://www.ukgbc.org/ukgbc-work/net-zero-carbon-buildings-a-framework-definition/ (2019)

[26]Crawford, R.H. Zero-emissions housing: the great impossible Australian dream? 44th annual conference of the architectural science association, ANZAScA 2010, Unitec Insitute of Technology, Auckland, New Zealand (2010)

[27]D. Birge and A.M. Berger. Transitioning to low-carbon suburbs in hot-arid regions: a case-study of Emirati villas in Abu Dhabi. Build. Environ., 147(2019)77-96,

[28]Satola D, Wiberg AH and Gustavsen A. Towards Zero Emission Residential Buildings (ZEBs) in a humid subtropical climate. analysis emissions from energy use and embodied emissions from materials in referential locations according to obligatory residential energy codes and using generic LCA data sources. In: Wang Z, Zhu Y, Wang F, Wang P, Shen C, Liu J, editors. Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019). Singapore: Springer Singapore; (2020)979–89.

[29]Stephan A and Stephan L. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. Appl. Energy, 280(2020)115932.

[32]Rivera ML, MacLean HL and McCabe B. 2021. Implications of Passive Energy Efficiency Measures on Life Cycle Greenhouse Gas Emissions of High-rise Residential Building Envelopes. Energy Build., (2021)111202.

[33]Lützkendorf T. Application of ‘element’-method in sustainability assessment. In IOP conference series: Earth Environ. Sci. Trans., 290(2019)012052.

[34]Luo XJ and Oyedele LO. Assessment and optimisation of life cycle environment, economy and energy for building retrofitting. Energy Sustain. Dev., 65(2021)77-100.

[35]Luo XJ and Oyedele LO. A data-driven life-cycle optimisation approach for building retrofitting: A comprehensive assessment on economy, energy and environment. J. Build. Eng., 43(2021)102934

[36]Luo XJ, Oyedele LO, Ajayi AO, Monyei CG, Akinade OO and Akanbi LA. Development of an IoT-based big data platform for day-ahead prediction of building heating and cooling demands. Adv. Eng. Inf., 41(2019)100926.

[37]Luo XJ, Oyedele LO, Ajayi AO and Akinade OO. Comparative study of machine learning-based multi-objective prediction framework for multiple building energy loads. J. Sustainable Cities Soc., 61(2020)102283.

[38]Luo XJ, Oyedele LO, Owolabi HA, Bilal M, Ajayi AO & Akinade OO. Life cycle assessment approach for renewable multi-energy system: A comprehensive analysis. Energy Convers. Manage., 224(2020)113354.

[39]Luo XJ, Oyedele LO, Akinade OO and Anuoluwapo OA. Two-stage capacity optimisation approach of multi-energy system considering its optimal operation. Energy AI, 1(2020)100005.

[40]Mousa OB, Kara S and Taylor RA. Comparative energy and greenhouse gas assessment of industrial rooftop-integrated PV and solar thermal collectors. Appl. Energy, 241(2019)113-123.

[41]Y Wang, M Li, R.H.E. Hassanien, X Ma and G Li. Grid-Connected semitransparent building-integrated photovoltaic system: the comprehensive case study of the 120 kWp plant in Kunming, China. Int. J. Photoenergy, (2018)6510487.

[42]Fan J, Chen Z, Furbo S, Perers B and Karlsson B. Efficiency and lifetime of solar collectors for solar heating plants. In 29th Biennial Solar World Congress of the International Solar Energy Society, (2009)331-340.

[43]Catalogue of European Urban Wind Turbine Manufacturers. European Commission under Intelligent Energy-Europe Programme.

[44]Moretti E, Barbanera M, Foschini D, Buratti C and Cotana F. Energy and environmental performance analysis of biomass-fuelled combined cooling and heating system for commercial building retrofit: An Italian case study. Energy Procedia, 101(2016)376-383.

[45]Longo S, Cellura M, Guarino F, La Rocca V, Maniscalco G and Morale M. Embodied energy and environmental impacts of a biomass boiler: a life cycle approach. AIMS Energy, 3(2015)214.

[46]https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021(last accessed 11 Oct 2021)

[47]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/997483/Quarterly_Energy_Prices_June_2021.pdf (last accessed 11 Oct 2021)

[48]https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh (last accessed 11 Oct 2021)

[49]https://www.greenmatch.co.uk/blog/2015/02/how-much-does-a-biomass-boiler-cost (last accessed 11 Oct 2021)

[50]https://www.insulationsuperstore.co.uk/product/kingspan-kooltherm-k5-external-wall-insulation-20mm-18m2-pack.html (last accessed 30 June 2021)

[51]Hammond G, Jones C, Lowrie E.F and Tse P. Embodied carbon. The inventory of carbon and energy (ICE). Version (2.0). 2011.

[52]Cardoso, A.A.M. Life Cycle Assessment of Two Textile Products Wool and Cotton. 2013.

[53]Mousa OB, Kara S and Taylor RA. Comparative energy and greenhouse gas assessment of industrial rooftop-integrated PV and solar thermal collectors. Appl. Energy, 241(2019)113-123.

[54]International Energy Agency (IEA), Methodology guidelines on Life Cycle Assessment of photovoltaic electricity. Photovoltaic Power Systems Programme, Report IEA-PVPS T 12-03, 2011.

[55]A.N. Karaiskakis, E.S. Gazis and G. Harrison. Energy and Carbon Analysis of Photovoltaic Systems in the UK. 28th European Photovoltaic Solar Energy Conference and Exhibition.

[56]Crawford RH. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renewable Sustainable Energy Rev., 13(2009)2653-2660.

[57]Kabir MR, Rooke B, Dassanayake GM and Fleck BA. Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation. J. Renewable Energy, 37(2012)133-141.

[58]Ardente F, Beccali G, Cellura M and Brano VL. Life cycle assessment of a solar thermal collector. J. Renewable Energy, 30(2005)1031-1054.

[59]Greening B. Life cycle environmental and economic sustainability assessment of micro-generation technologies in the UK domestic sector. The University of Manchester, United Kingdom, 2014.

[60]Gazis E and Harrison GP. June. Life cycle energy and carbon analysis of domestic combined heat and power generators. In 2011 IEEE Trondheim PowerTech, IEEE, (2011)1-6.

[61]Longo S, Cellura M, Guarino F, La Rocca V, Maniscalco G and Morale, M. Embodied energy and environmental impacts of a biomass boiler: a life cycle approach. AIMS Energy, 3(2015)214.